NLF Potential of Long Range Aircraft using CATNLF design and different stability theories

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Aim of this work:

for long range aircraft (LR aircraft) & **free flight conditions**:

Using different stability theories

- Design of natural laminar flow **limit** (NLF) airfoils using CATNLF
- 3D NASA CRM-NLF model
- Estimate NLF potential

Outline:

- Introduction and Background
- Results
  - Tapered wing airfoil design
  - 3D NASA CRM-NLF wing body configuration
- Summary

*Partially results here presented were also presented in AIAA Aviation 2020, AIAA 2020-2748

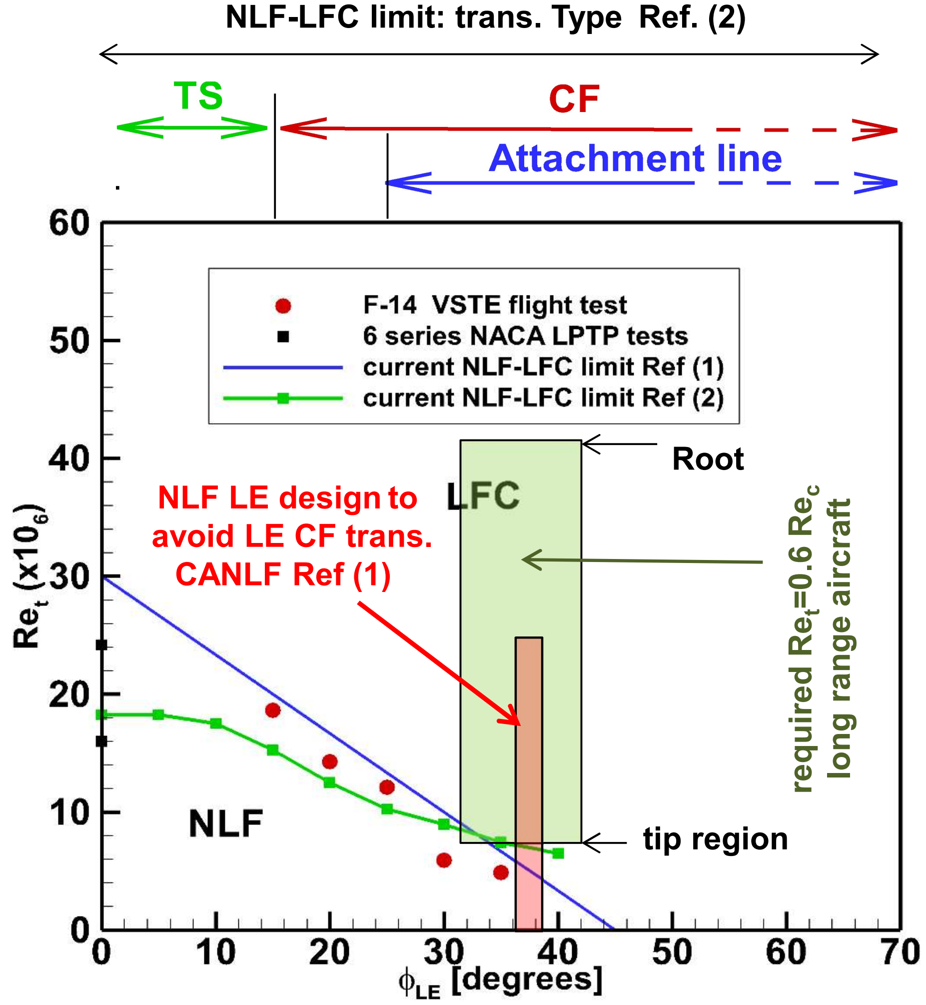
Limits of laminar flow: NLF–LFC boundary & long r. aircraft

- **Transition at boundary due to different instabilities or to combination of them**

- **Longe Range aircraft**
  *** large LE sweep, ϕ_{LE} > 30°**
  *** large Re_c numbers**
  *** fly faster $M_\infty \geq$ 0.82**

  => suction required to avoid LE trans. (CF & attachment inst.)

- **Special LE design, CATNLF, Ref. 1**
  Crossflow attenuated NLF design
  no suction req., NLF possible

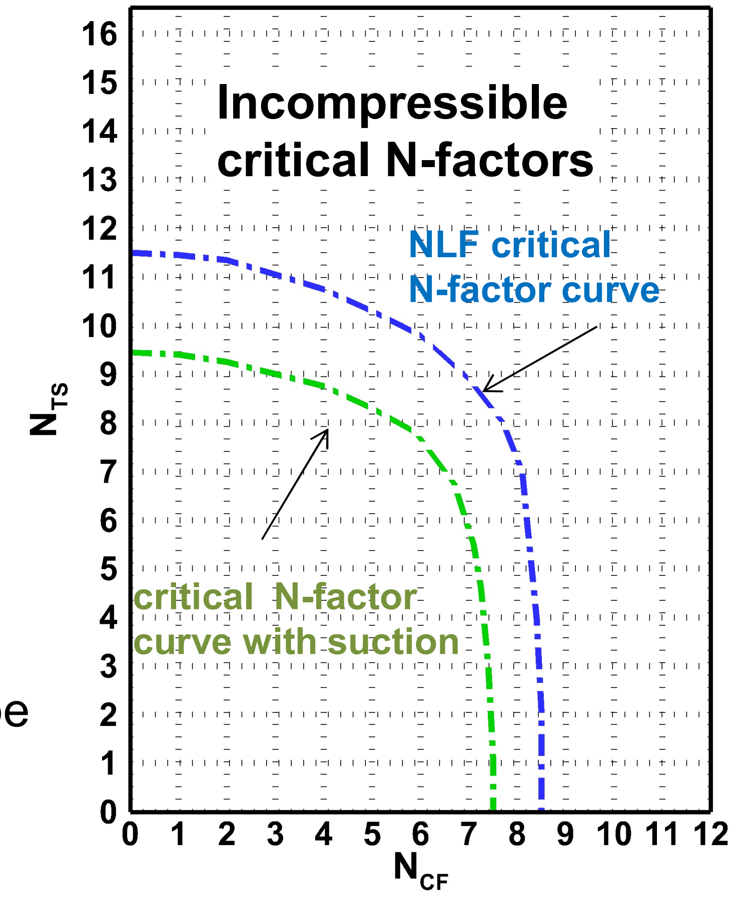


(1) R. Campbell et al, AIAA 2016-4326, AIAA 2017-3059
2) Géza Schrauf, AIAA 2008-3738 (uses Re_c, here assumed Re_t=Re_c*0.5

Stability analysis : LST for N_{CF} N_{TS}, critical N-factors

Stability Analysis:

- Based on compressible BL input
- Local, incompressible or compressible
- LST code: LILO
- TSI in local flow direction
- CFI for f=0 Hz, (here const. λ-strategy used)

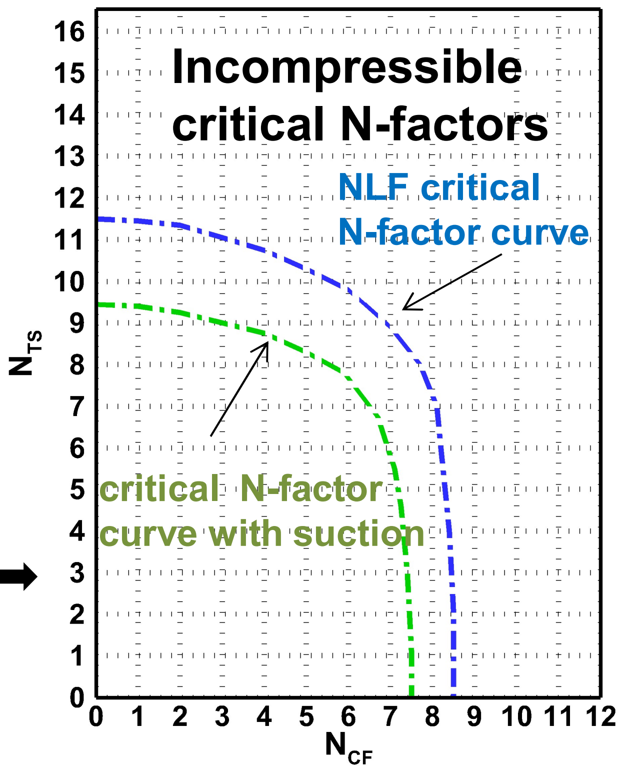


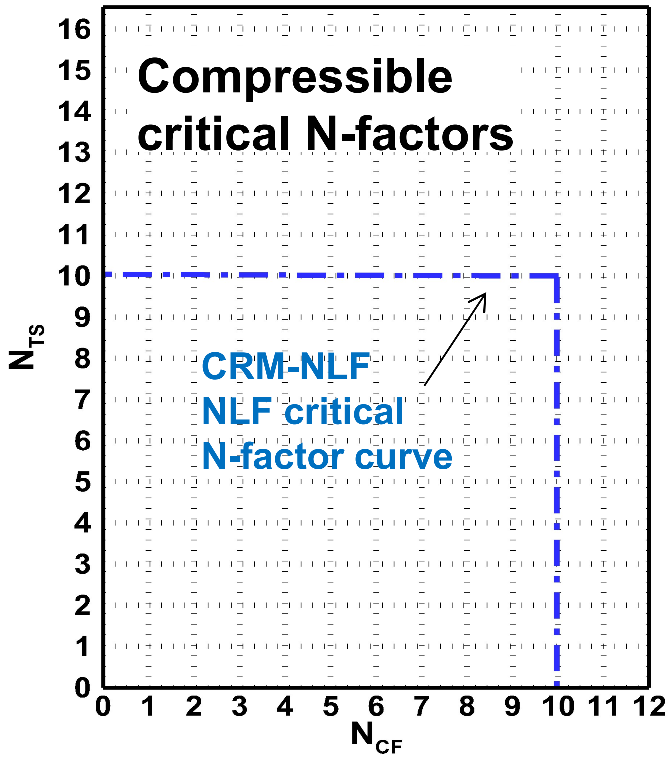
Critical N-factors

- Obtained with flight tests and WT experiments
- have to be determined for each stab. theory type
- diff. groups use (predominantly) different LST:
  - DLR & Airbus: incomp. LST,
  - NASA & ONERA: comp. LST

LST, free flight critical N-factors and LRA Mach numbers

Used free flight crit. N-factors in this work

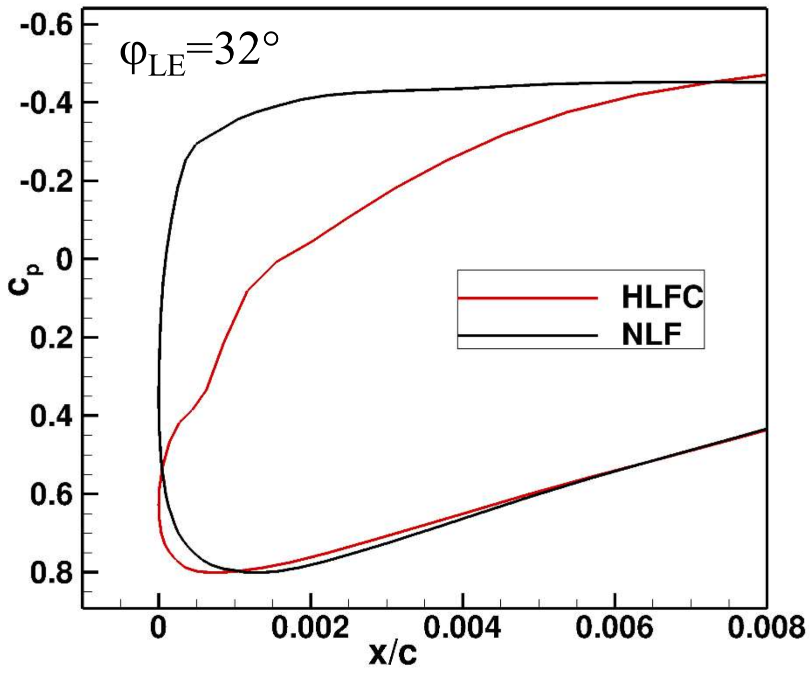


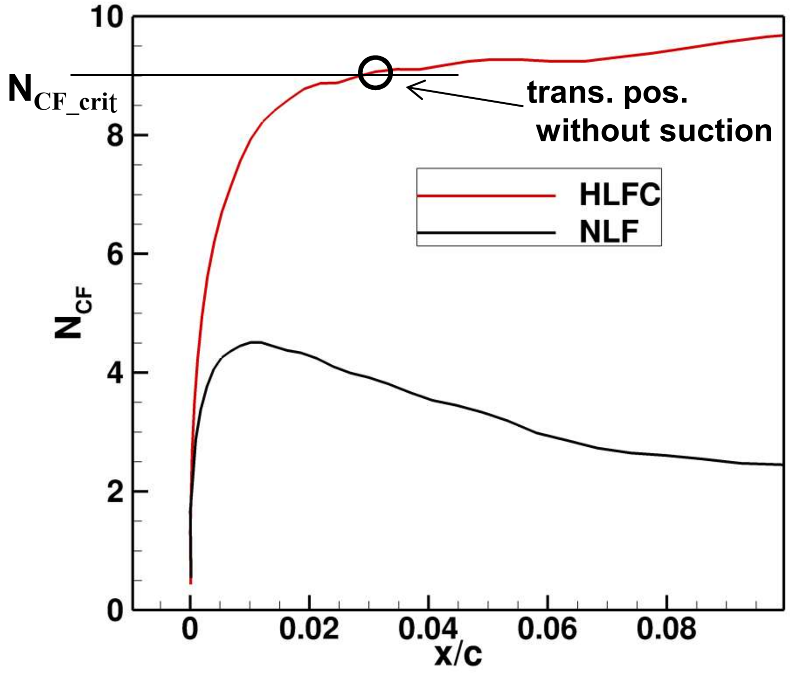


- Compressible LST shows a stabilizing (?) effect on N_{TS} with increasing Mach number
- Flight data: obtained for middle range aircraft i.e. $M_\infty < 0.80$
- **long range aircraft cruise: $0.82 < M_\infty < 0.86$, no free flight crit. N-factors here in the wing supesonic region M reaches values of 1.2-1.3**
  - N_{TS} comp. & incomp. significantly different results
  - Using comp. or incomp. LST with corresponding critical N-factors (from lower flight tests) for LRA leads to different NLF potential

Large LE-sweep CATNLF: NLF Airfoil A design (LE region design)

M_∞=0.83, C_L=0.546 and $Re_c=23\cdot10^6$, tapered wing airfoil





- Tapered airfoil design (2.75D), φ_{LE}=32° φ_{TE}=21°
- N-factors obtained with incompressible LST
- N_{CF} reduced from 8.5 (HLFC airf.) to 4.2 (NLF airfoil)

(1) R. Campbell et al, AIAA 2016-4326, AIAA 2017-3059
(2) G. Redeker et al, Journal of Aircraft, Vol.25. No.7 Jul. 1988

NLF limit airfoil design for upper wing

In the region up to the shock design airfoil with C_p which satisfies

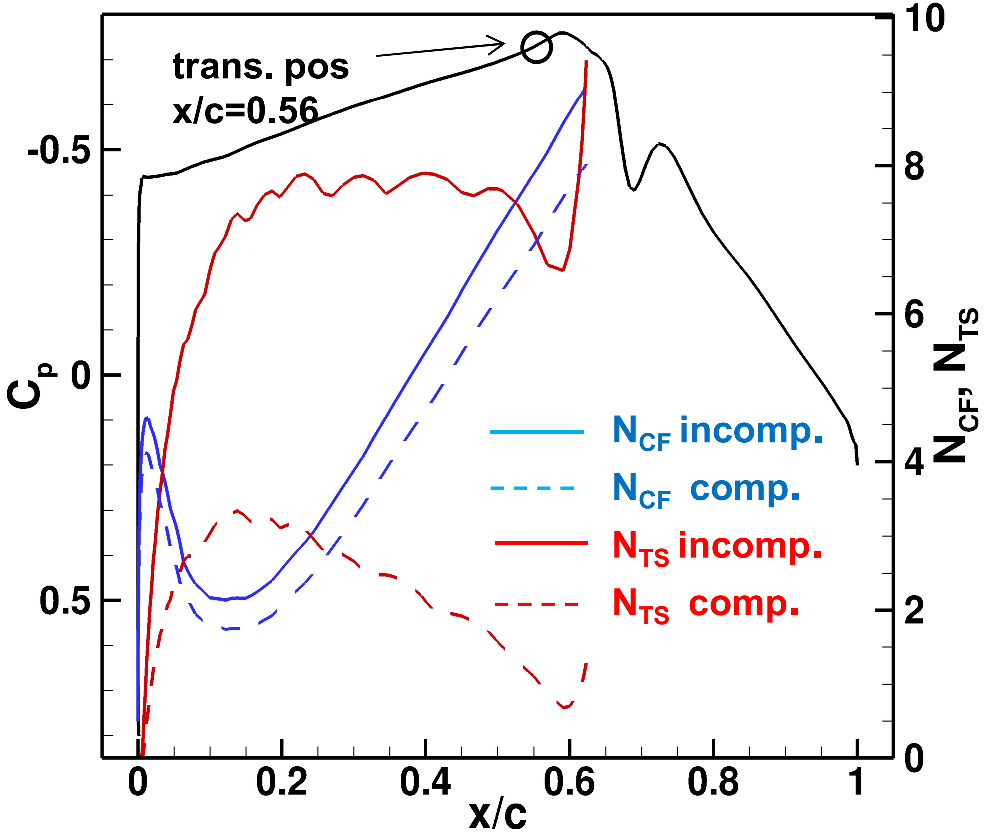
- max N_{TS}, max N_{CF} are just below critical N-factor values
- shocks are small

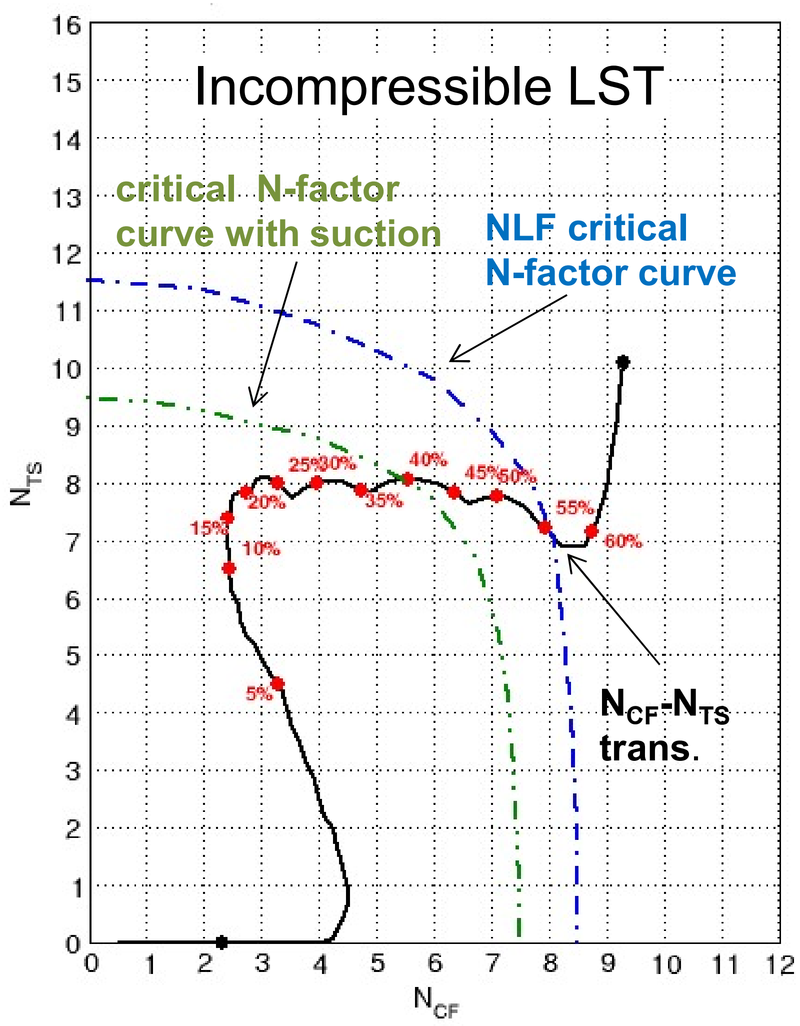
For a wing which has such a limit C_p distribution in a given wing section:

- outboard of this section: NLF laminar BL up to the shock
- inboard of this section: transition position moves to the nose

Incompressible NLF limit airfoil A: CATNLF & middle chord design

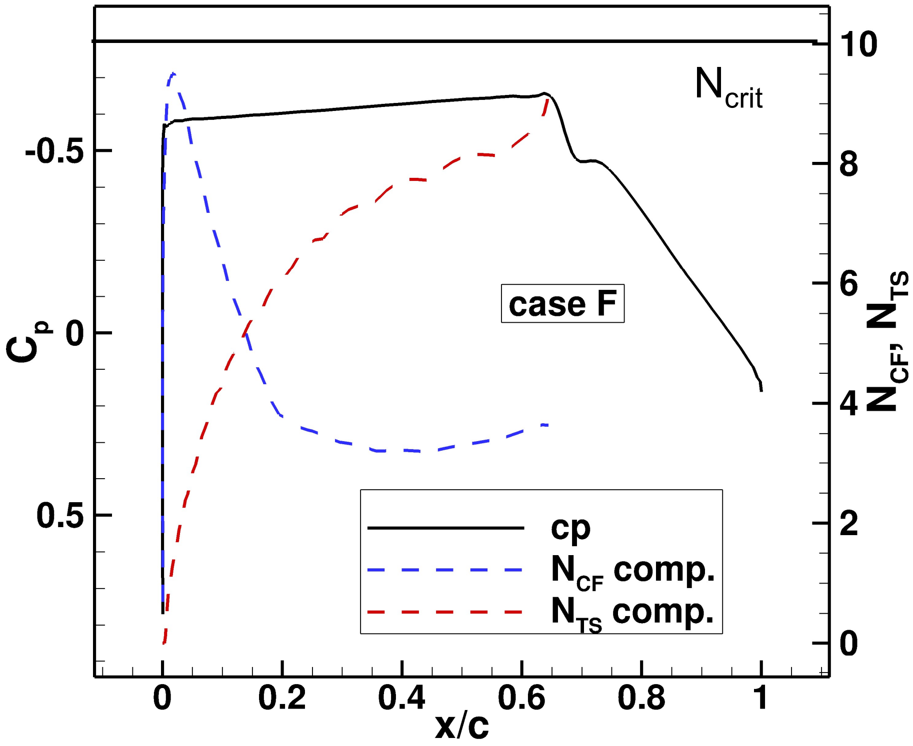
M_∞=0.83, C_L=0.546 and Re_c=23·10^6, tapered wing airfoil φ_{LE}=32° φ_{TE}=21°

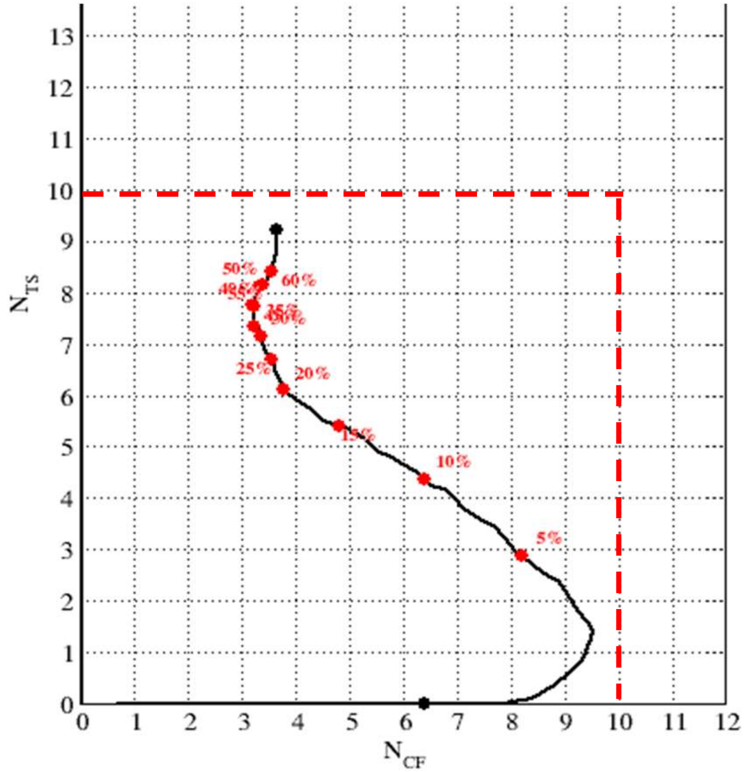




- comp. N_{TS} < incomp. N_{TS} (ϕ=0°)
- comp. $N_{CF} \approx$ incomp. N_{CF}
- Incomp. LST: mixed type trans.
- comp. LST: trans at shock, sep.

compressible NLF limit airfoils E & F : CATNLF & middle chord design ϕ=0°





M_∞=0.83, C_L=0.546, φ_{LE}=32°, φ_{TE}=21°

Case E: $Re_c=40\cdot10^6$, $Re_T=26.0\cdot10^6$
Case F: $Re_c=35\cdot10^6$, $Re_T=22.8\cdot10^6$

	incomp.	comp.
Airfoil	A	E(F)
$Re_c/10^6$	23	40(35)
$Re_t/10^6$	13	26(23)
c_{D_wav} (d.c.):	6.54	0.76
Trans. Type	mixed	TS

LRA NLF limit airfoils compressible & incompressible

- Nose region: no CF transition thanks CATNLF (comp. & incompressible)
- Middle chord up to shock: compressible design different to incompressible one*

	incomp.	comp.
Airfoil	A	E(F)
$Re_c/10^6$	23	40(35)
$Re_t/10^6$	13	26(23)
c_{D_wav} (d.c.):	6.54	0.76
Trans. Type	mixed	TS

For middle range aircraft designs compressible& incompressible are similar

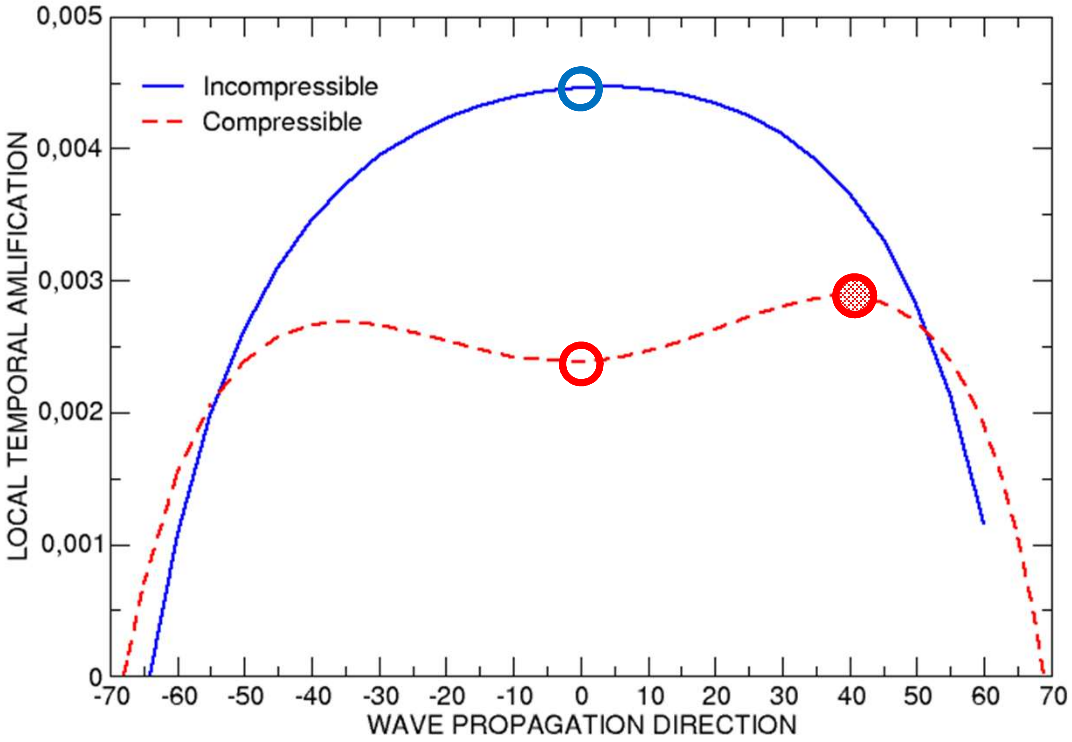
compressible NLF limit airfoil F : local amplification rate

Case F Re_c=35·10^6 , M_∞=0.83, C_L =0.546, φ_{LE} =32, φ_{TE} =21°

Local amplification rates
at one station in the boundary layer
for several wave propagation directions

X/C 0.163
Local Mach 1.13

Largest amplication rate at φ= 40°



*Results in this slide from G. Schrauf's presentation in this workshop

compressible NLF limit airfoil F : most amplified TS modes for ϕ=40°

Case F

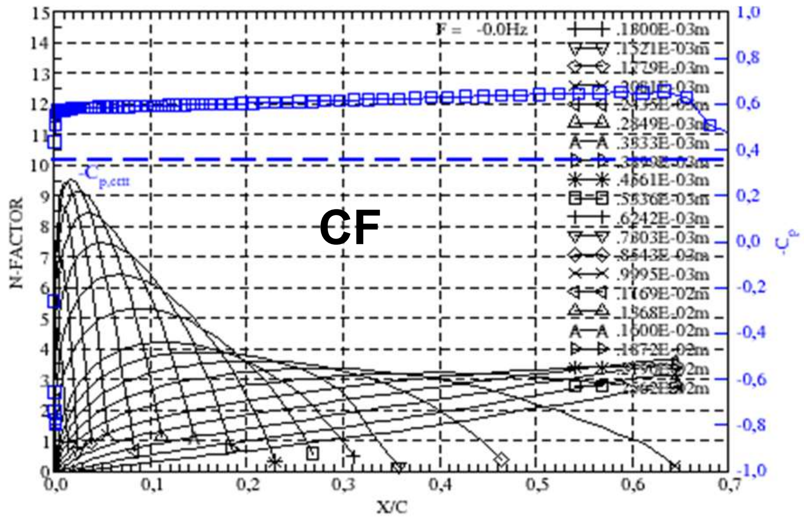
$Re_c = 35 \cdot 10^6$

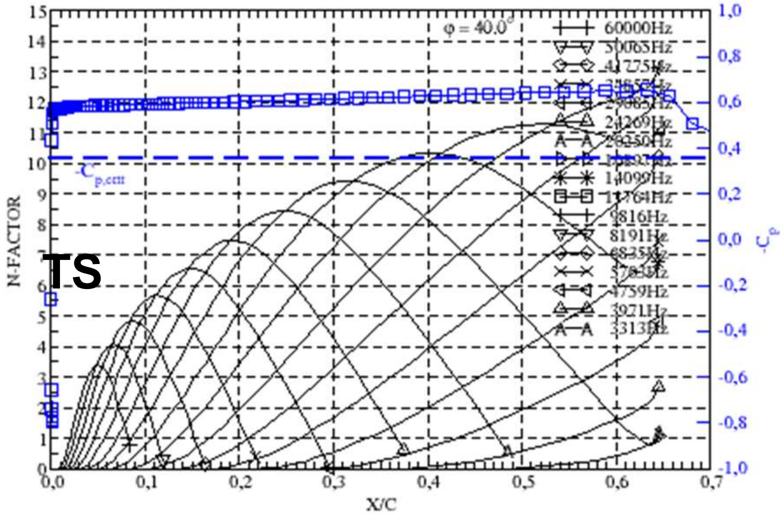
$M_\infty = 0.83$

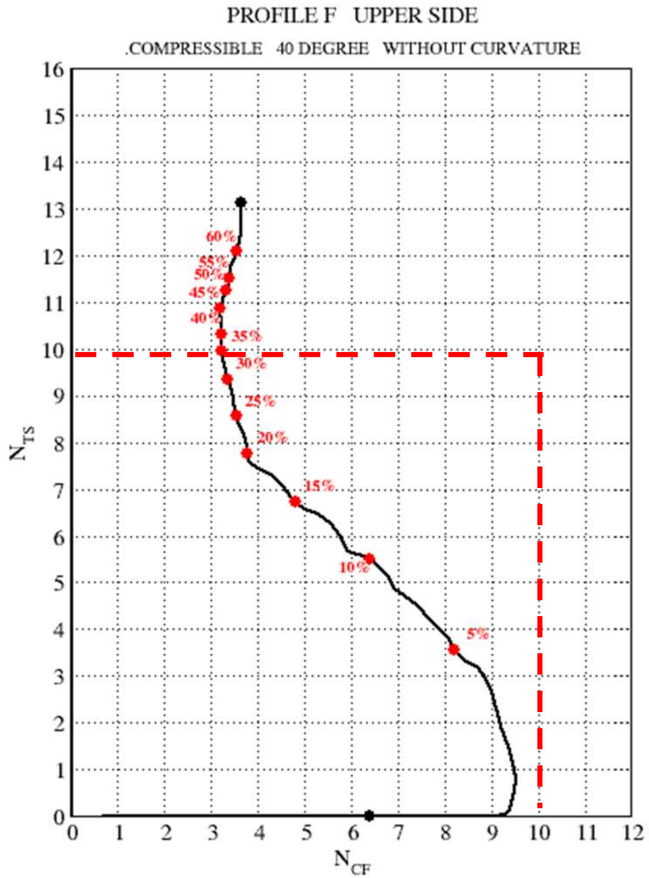
$C_L = 0.546$

$\varphi_{LE} = 32°$

$\varphi_{TE} = 21°$





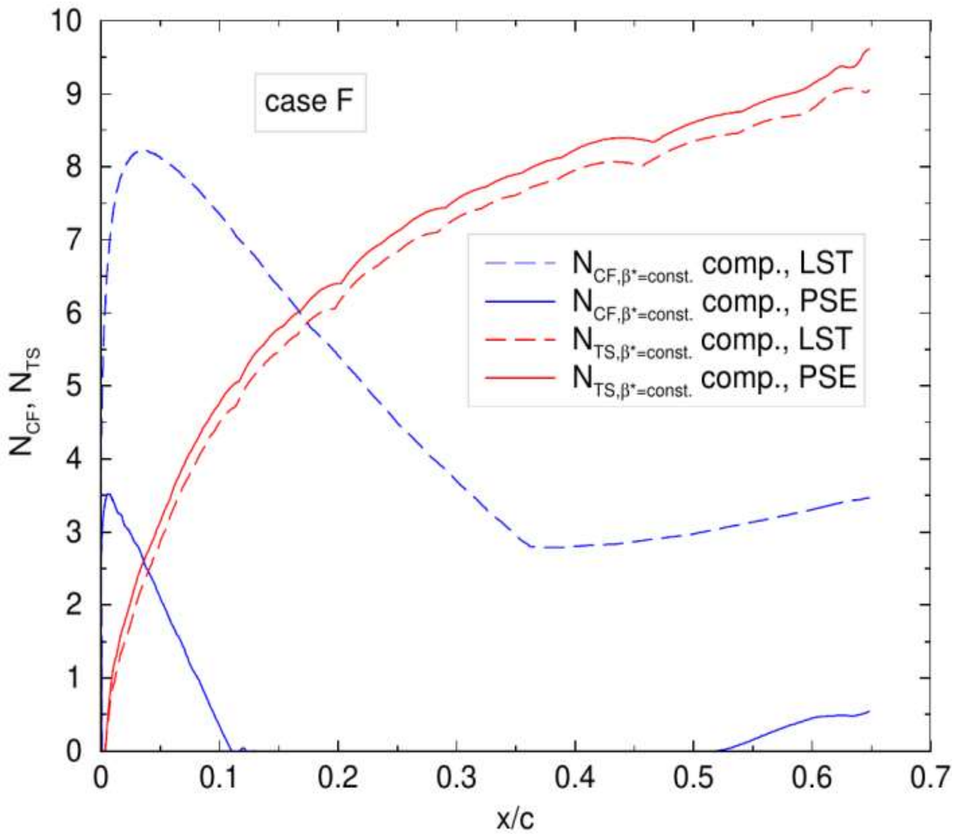


	ϕ=0°	ϕ=40°
$Re_t/10^6$	23	11.55
x_t/c	0.65	0.33

*Results in this slide from G. Schrauf's presentation in this workshop

Beyond LST: PSE results for compressible limiting Airfoil case F

M_∞=0.83, C_L=0.546, φ_{LE}=32° φ_{TE}=21°
Case F: $Re_c=35\cdot10^6$, $Re_T=22.8\cdot10^6$



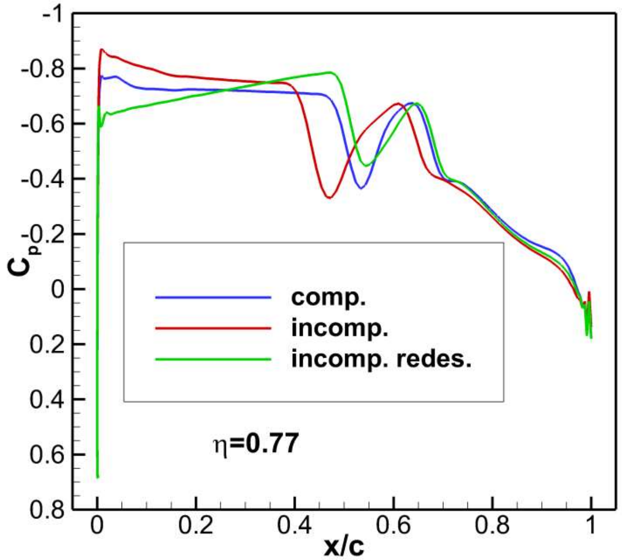
Stability Analysis:

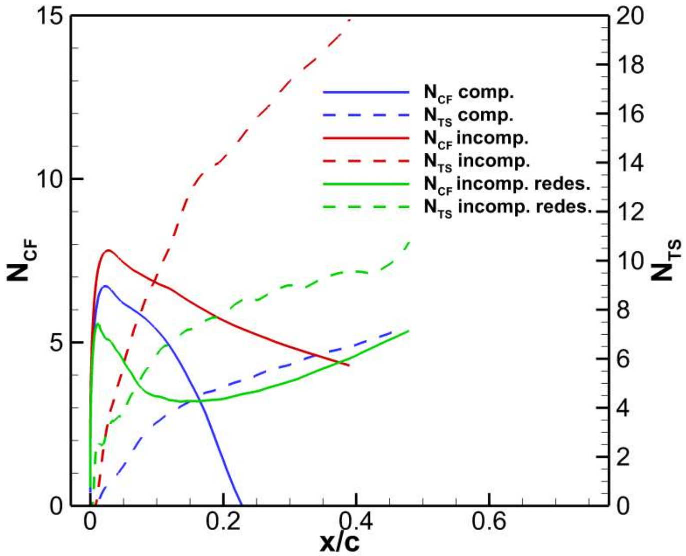
- Based on compressible BL input
- nonlocal compressible
- PSE code: NOLOT/PSE
- Strategy: Constant spanwise wavenumber ß*
- Takes into account nonlocal and surface curvature effects

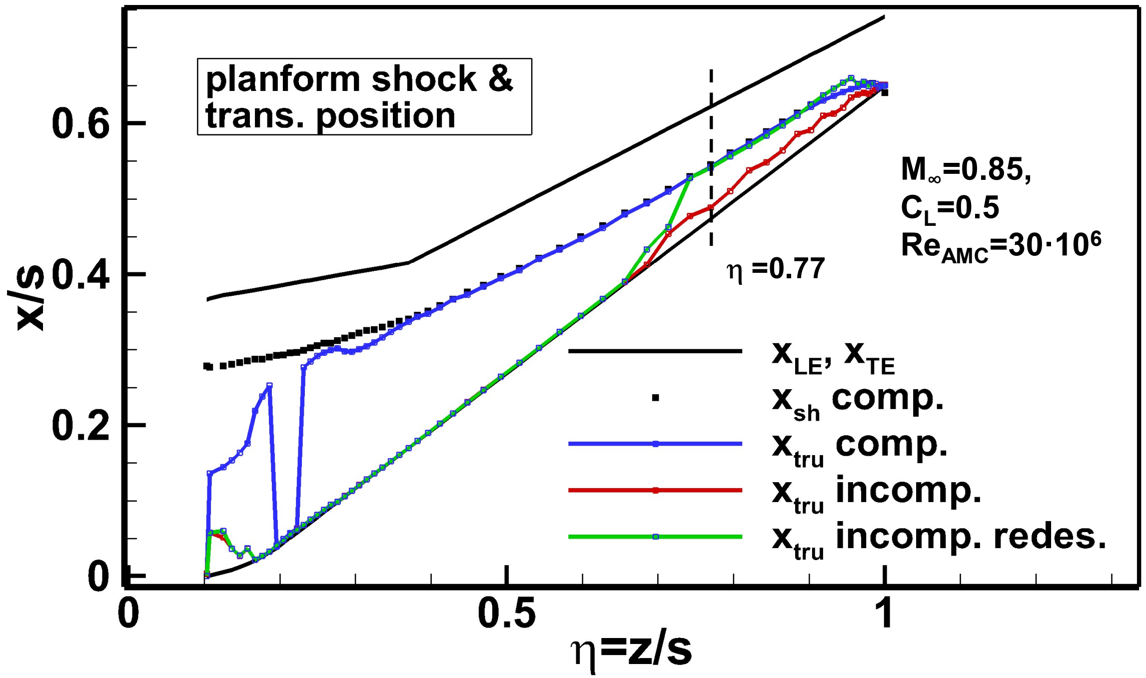
N_{TS}: PSE and LST results similar

N_{CF} : PSE shows significant reduction.
Is crossflow instability overestimated in LST?
In the LE region, is there further NLF potential beyond the one of airf. E & F?

3D transition location (2) : NASA common research model CRM-NLF







no trans. due to ATI: $101 < Re_\theta < 235$, for $\eta > 0.4$, $Re_\theta < 110$

compressible LST:

- except for root sec. region, trans. close to shock

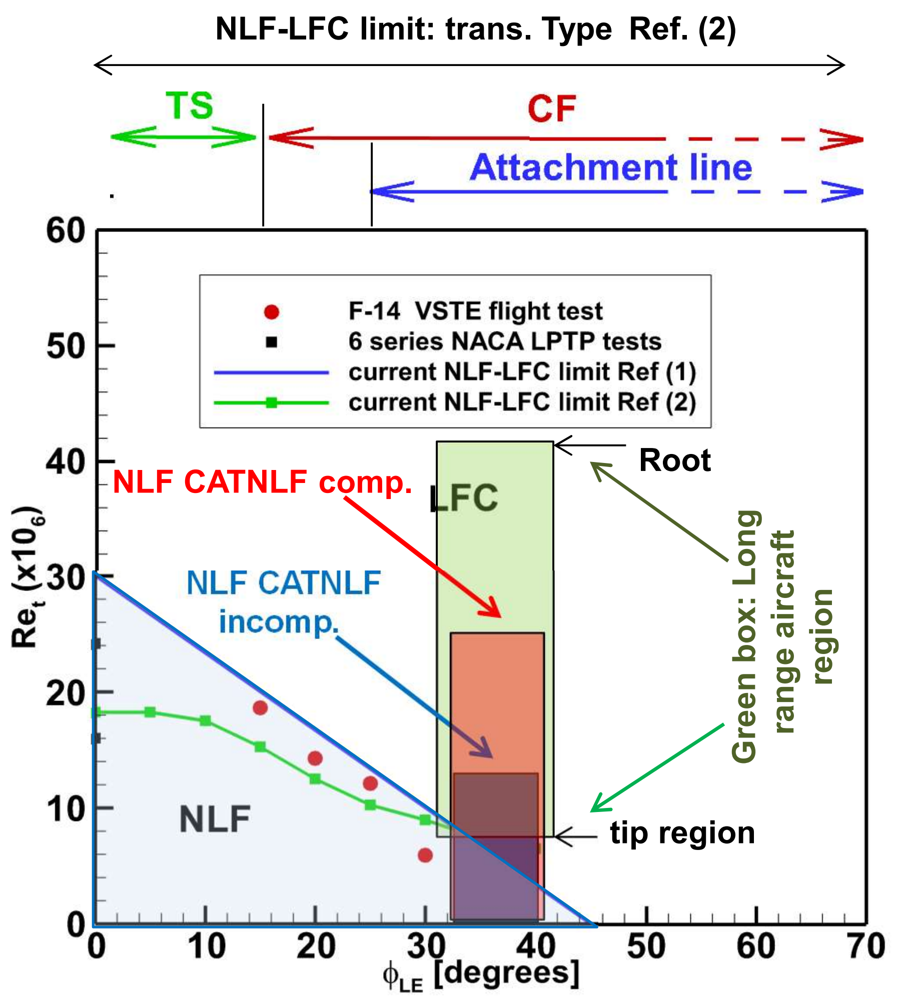
incompressible LST:

- for $\eta < 0.7$, trans. at LE due to CFI
- for $\eta > 0.7$, trans. close to LE due to TSI
- redesign: for $\eta > 0.73$, trans. close to shock

DLR

Summary: free flight limits of NLF for LR aircraft

- Critical N-factors are **not available for LR-aircraft** cruise cond.. Currently for LST, values from flight tests for lower Ma are assumed.
- Results confirm that **CATNLF extends NLF limit** into a region previously assumed as LFC, indepently from comp. or incomp. LST
- Incompressible and compressible LST lead to **different wing designs** with **different NLF potential**, with compressible LST leading to:
    - larger Re_t
    - less c_{d_wav}
- **flight test with LR-aircraft cruise conditions** are necessary to obtain reliable critical N-factors & NLF limits
- **CATNLF airfoil design is also useful for HLFC airfoils**, since attenuated CFI requires less suction. This is important since for LR aircraft HLFC will still be required



OUTLOOK

- NASA * has designed a test article for tests with LR aircraft cruise conditions using a F-15 testbed *

- New flight test will provide the critical N-factors. They will show which of the current NLF limits: compressible or incompressible are closer to reality

- Impact of CATNLF at high lift has to be considered

- CATNLF potential for middle range aircraft has to be explored. Currently laminar DLR-BSW design requires HLFC for inner wing and has reduced cruise Mach number compared to laminar DLR-FSW**

- Stability theory beyond LST which is expensive, but contains more physical modelling has to be used to better assess the current NLF limits. Some PSE results were given in the paper

* **M. Lynde, R. Campbell, B. Hiller, L. Owen, AIAA 2021-3292**

** **T. Streit et al , Aeronautical J, 2015**

THANK YOU